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SUMMER RESEARCH TECHNICAL REPORT

Digital Image Correlation of Flapping Wings for Micro-Technologies

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The unpredictable, and therefore inherently dangerous, situations warfighters experience have created a demand for advanced environmental knowledge of impending threats. Small, stealthy, and versatile micro-technologies have great potential in this area and can provide autonomous reconnaissance and nonlethal protection while either crawling or flying. One particular challenge with flying systems is designing a lightweight vehicle while maintaining critical function performance. This project focuses on using digital image correlation software and high-speed cameras to analyze lightweight flapping wings for micro-system use. To understand the parametric design space, a design of experiments is created, varying wing span, chord, shape, and spar count. Then the wings are manufactured using a three-dimensional printer and thin plastic sheeting. A custom-made load cell measures the thrust and lift of the speckled wings, which are mounted on and powered by a bimorph actuator. The stereo setup assesses the wing?s speckle pattern and measures the change in light intensity, which correlates to wing structure movement or deformation. This enables the calculation of important wing parameter trends, including strain, position, velocity, and acceleration. Computational modeling verifies these results while identifying design features that enhance flight performance and support a lightweight and efficient micro-system design.

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Abstract

The unpredictable, and therefore inherently dangerous, situations warfighters experience have created a demand for advanced environmental knowledge of impending threats. Small, stealthy, and versatile micro-technologies have great potential in this area and can provide autonomous reconnaissance and nonlethal protection while either crawling or flying. One particular challenge with flying systems is designing a lightweight vehicle while maintaining critical function performance. This project focuses on using digital image correlation software and high-speed cameras to analyze lightweight flapping wings for micro-system use. To understand the parametric design space, a design of experiments is created, varying wing span, chord, shape, and spar count. Then the wings are manufactured using a three-dimensional printer and thin plastic sheeting. A custom-made load cell measures the thrust and lift of the speckled wings, which are mounted on and powered by a bimorph actuator. The stereo setup assesses the wing's speckle pattern and measures the change in light intensity, which correlates to wing structure movement or deformation. This enables the calculation of important wing parameter trends, including strain, position, velocity, and acceleration. Computational modeling verifies these results while identifying design features that enhance flight performance and support a lightweight and efficient micro-system design.

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Student Bio

I am a second-year graduate student at the Georgia Institute of Technology in the Aerospace Systems Design Laboratory. I received my bachelor's degree in aerospace engineering from The University of Michigan, Ann Arbor. My interests at Georgia Tech include systems engineering analysis of the U.S. Army Research Laboratory's micro-autonomous technologies as well as designing processes and methods for optimizing the engineering collaborative design process for the Office of Naval Research. I have also been involved in researching heat shields and several other entry, descent, and landing projects at the National Aeronautics and Space Administration Jet Propulsion Laboratory. During my free time, I am involved in community service regarding healthy diets for the elderly and disabled, and have served as a tutor for grade school students. I enjoy playing the tuba in the Georgia Tech Pep Band, playing classical piano, reading science fiction books, and jogging.

1. Introduction and Background

Micro air vehicles (MAVs), as defined by the Defense Advanced Research Projects Agency (*1*), are maneuverable aerial robotic mechanisms that weigh <100 g and are smaller than 150 mm. MAVs are of great interest to the military because in life-threatening situations, they have the potential to scan, gather, and relay critical information back to the unit commanders. MAV missions could include interior reconnaissance, convoy assistance, nonlethal protection, biochemical sensing, and deployment of light payloads.

MAV research is difficult due to vehicle requirements; the vehicle must be small, lightweight, and expendable, while maintaining the endurance and stealth required for these missions (*2*). Many aerodynamic issues arise when operating at low Reynolds numbers as well as difficulties computationally modeling the thin wing skin. Due to these issues, no MAVs exist that operate with the precision and efficiency of insects; investigating MAVs is an incredibly intriguing field to many researchers.

Whereas most motion capture systems are costly and permanent, digital image correlation (DIC) is an alternative that can be temporary, faster, and less expensive. DIC is a displacement measuring technique that uses a large number of images that are taken during the loading of a specimen. The concept behind DIC is simple and only holds two assumptions. First, the motion of the object in the images directly corresponds to the actual test specimen, and second, the object has adequate variations in light intensity. The software is capable of acquiring, interpreting, and analyzing the variations in light intensity reflected from a surface pattern, referred to as speckle. Any change in light intensity at a given point on the object correlates to structure movement and deformation. If the light intensity from the speckle remains constant, then any movement is purely translational; this can be resolved into the position, velocity, and acceleration of the specimen over time. However, a variation of light intensity correlates to material deformation at this point, which can be resolved into strain.

DIC analysis can be done with a single camera; however, adding another camera enables three-dimensional (3-D) analysis of the system, which is desirable for flapping wings because of their rotational movements. The DIC system used in this project is the Vic-3D, which will resolve the wing motion, allowing the strain, position, velocity, and acceleration to be calculated. The Vic-3D setup is simple and allows the cameras to be anywhere from 15° to 45° apart to obtain stereo viewing. The software (*3*) is extremely useful because it is simple to set up and is capable of interpreting the data from both cameras and compiling in order to attain a complex 3-D stereo image of the test subject.

The flapping wings will be mounted on a layered Pb(Zr0.55Ti0.45)O3 lead zirconate titanate (PZT) bimorph actuator (*4, 5*). Electrical currents sent through the actuator's lead-based

piezoelectric material results in a few millimeter displacement of the material tip at frequencies up to 200 Hz. The tip of the actuator material is connected by a simple lever to the wing base, as shown in figure 1, which dissipates practically no power. The frequency of the current is tuned to vary the wing-flapping frequency and is generally adjusted to match the wing resonant frequency for maximum tip displacement (around 5 to 30 Hz). The small displacement in the actuator material is amplified at the wing tip; at resonant frequencies, the actuator can provide wing-flapping angles up to 70°.

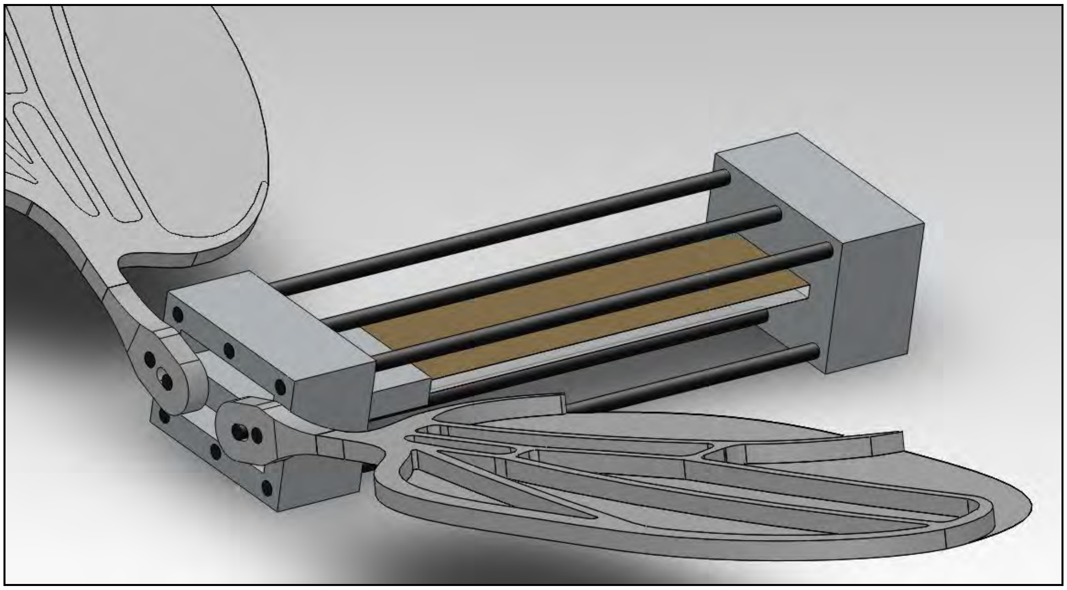

Figure 1. Wing lever mechanism.

The wing actuator base is clamped to a load cell custom designed to measure the experienced thrust and lift. Piezo-resistive semiconductor strain gages are used because of their small size and high sensitivity. The load cell design is optimized to be sufficiently sensitive in resolving very small forces while also maintaining adequate stiffness to avoid natural frequencies near those of the flapping wings. A detailed overview of the load cell design process can be found in section 2 of this report.

To determine the wing configurations to be tested, a design of experiments (DOE) is created varying the wingspan, chord, shape, and number of spars. Twelve sets of wings are manufactured using a 3-D printer for the structure and a thin plastic sheet for the skin. The use of a strobe light to capture the wing movement with fewer frames per second was considered; however, for simplicity, a Photon high-speed video camera is used instead. The load cell strain gages are linked to a voltage meter to record the resulting thrust and lift generated from the flapping wings. After the load cell and DIC data has been processed, trends between design parameters and wing performance are analyzed and compared to similar research results. Results are also validated by detailed wing runs and computational analysis results; details of these aspects can be found in section 2 of this report.

2. Experiments and Calculations

The process of this project consisted of several defining steps. First, load cell designs and methods are researched to understand characteristics required to resolve small forces; this information is used to design and manufacture the load cell. Concurrently, design characteristics of past studies and future areas of interest are compiled to create a flapping wing parametric design space. Next, using the design space, we designed and manufactured a set of test wings. Last, the flapping wings are set up, and high-speed cameras are used to gather information for the DIC software. The load cell is then used to gather forces data. The coupling and comparison of the final sets of data are discussed in section 3 of this report.

2.1 Load Cell Design and Manufacturing

Load cells generally consist of a beam with strain gages attached as specific points. The strain gage conductor is stretched or compressed when the material is deformed, changing its resistance. This resistance can be measured by the resulting change in voltage, which correlates to the strain in the material. The equation for engineering strain is shown in equation 1, where ε is the engineering strain, L_0 is the initial length, and L_1 is the final length.

$$\varepsilon = \frac{(L_1 - L_0)}{L_0}. \tag{1}$$

Piezo-resistive semiconductor strain gages are ideal for the flapping wing application because they are small, measuring only 0.008 in wide, and have high sensitivity, more than 50 times greater than that of foil gages. However, due to the high changes in gage resistance, care must be taken when using semiconductor gages with the Wheatstone bridge, shown in figure 2. The Wheatstone bridge is characterized by equation 2. The strain measurement from the Wheatstone bridge circuit is shown by equation 3 and is dependent on the gage factor (GF).

$$V_{out} = V_{in}\left[\frac{R_4}{R_4+R_2} - \frac{R_3}{R_1+R_3}\right]. \tag{2}$$

$$\varepsilon = {}^{\frac{\Delta R_2}{R_2}}\!\Big/_{GF}\,. \tag{3}$$

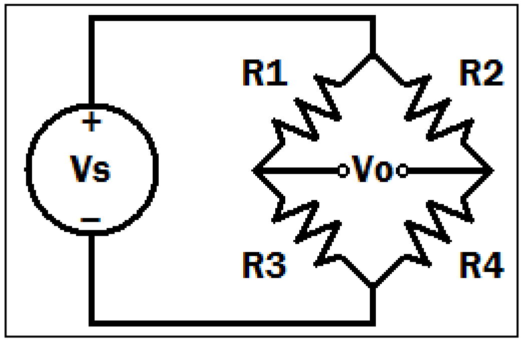

Figure 2. Wheatstone bridge circuit.

Micron Instruments SS-060-033-1000P-S1 practice strain gages were applied to 16 locations on the load cell, as shown in figure 3. The load cell is designed to be sensitive in the corresponding lift and thrust directions, where no lateral force is expected because of symmetrical wings. The final design features create a balance between system sensitivity and stiffness. The system must have adequate sensitivity to resolve small forces but enough stiffness to avoid low natural frequencies near those of the flapping wings (5 to 30 Hz). The final load cell design, shown in figure 4, is computer numerical control manufactured from 6065 aluminum, can resolve forces down to 0.1 g, and has a first-order natural frequency around 90 Hz.

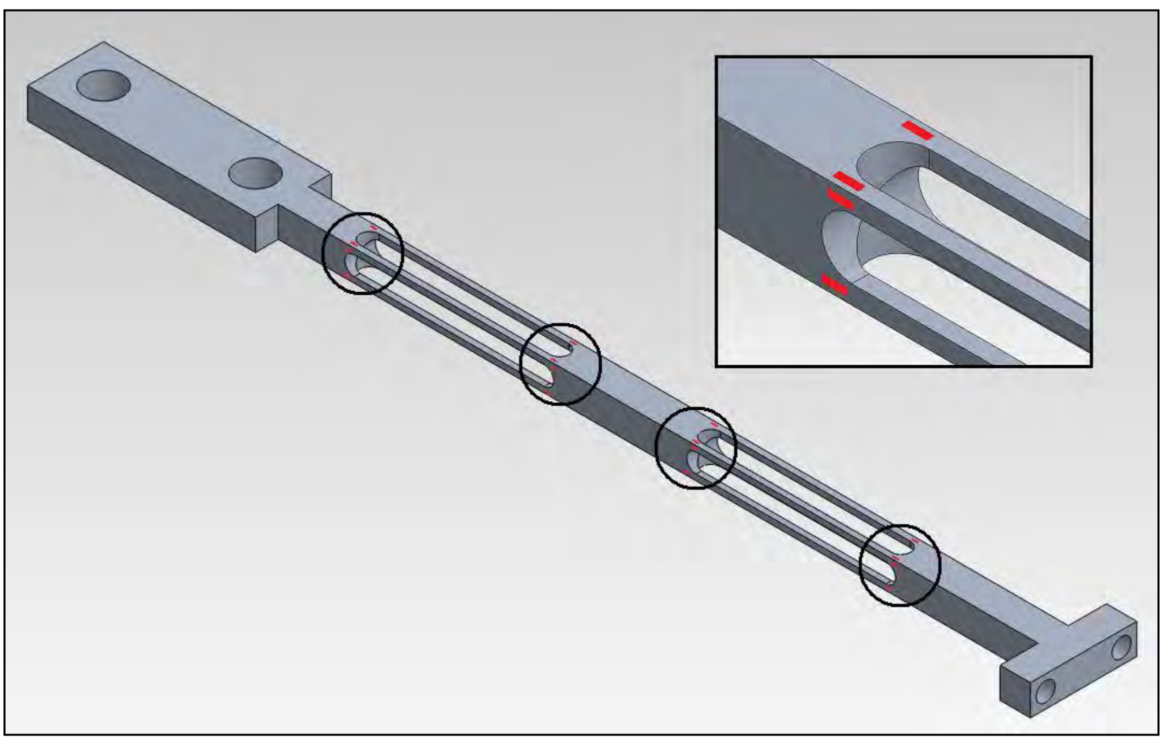

Figure 3. Strain gage locations.

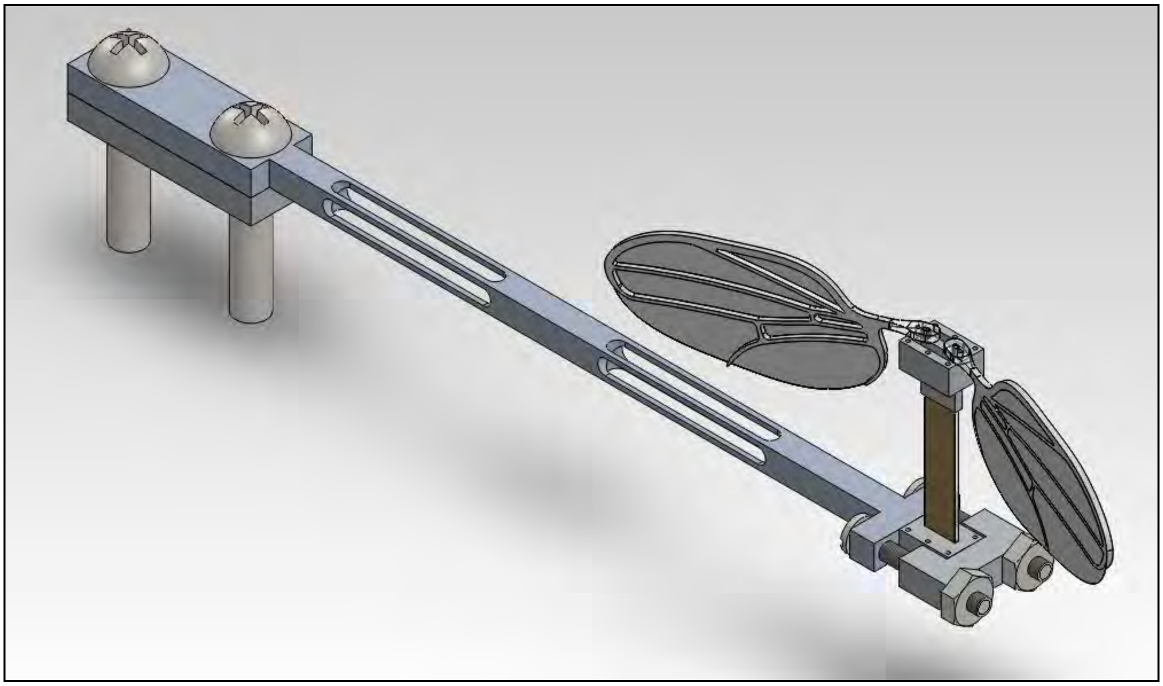

Figure 4. Final load cell design with actuator and wings.

2.2 Design Space and Design of Experiments

The parametric design space is a compilation of previously researched wing designs as well as design characteristics that may be of future interest. Three main wing shapes have been researched in the past: wing shape 1 is based off the wing of a locust, wing shape 2 is based off Kumar's balsa wood design (*6*), and wing shape 3 is based off the drosophila wing. These three wing types are used as a starting point in the wing design for this project and are shown in figure 5. The wingspan varies between 3.5 and 5.5 cm, the wing chord varies between 1 and 3 cm, and the spars vary from zero to two. When parameters from previous studies are used, it is important to keep the Reynolds number accurate depending on the test size and fluid viscosity. Reynolds number is dependent on chord length l, velocity U, and kinematic viscosity ν, shown in equation 4.

$$Re = \frac{lU}{\nu}. \tag{4}$$

Figure 5. Wing shape inspirations: locust (left), balsa (center), and drosophila (right).

The DOE is determined using Taguchi's L_9 orthogonal array, allowing the four parameters to each have three levels, as shown in table 1. This array results in 9 test runs, shown in figure 6, rather than 81 tests if done using the full factorial. Three additional tests were added to the test plan: two to test rectangular shape and confirm material deformations known from Kirchhoff-Love flat plate bending theory and one design that includes a large-scale version of the drosophila wing vein structure, shown in figure 7. With this experimental data, response surface methodology (RSM) will be used to explore the relationship of the design parameters to the experimental outputs. JMP statistical software will be used for the RSM analysis.

Table 1. Wing shape DOE.

Run	Shape	Chord (cm)	Half Span (cm)	Spars
1	Locust	1	4.5	0
2	Locust	2	5.5	1
3	Locust	3	6.5	2
4	Balsa	1	5.5	2
5	Balsa	2	6.5	0
6	Balsa	3	4.5	1
7	Drosophila	1	6.5	1
8	Drosophila	2	4.5	2
9	Drosophila	3	5.5	0

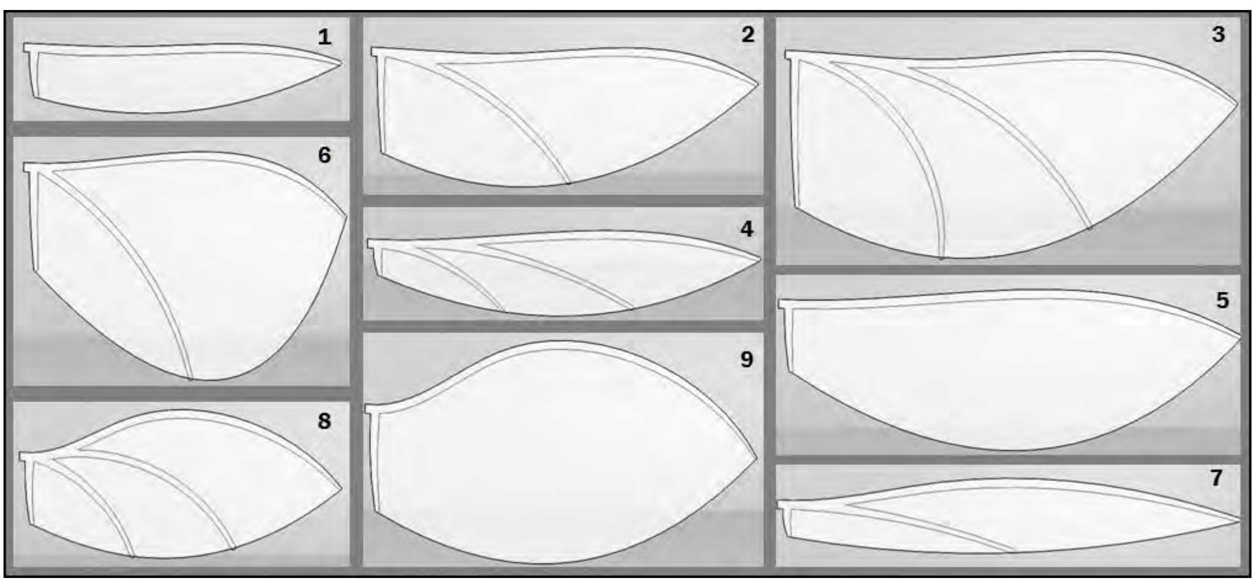

Figure 6. DOE wing models.

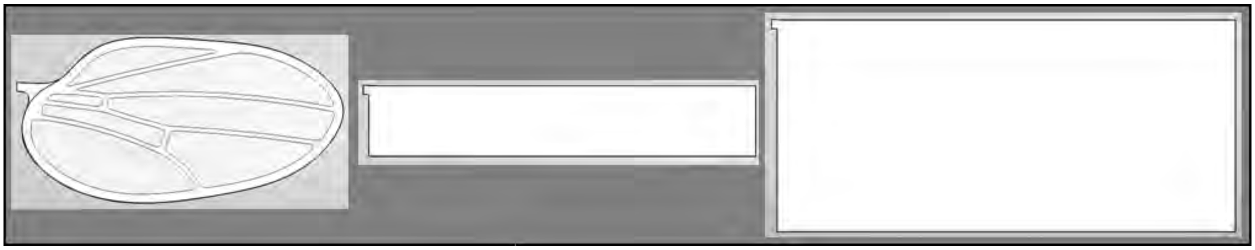

Figure 7. Additional wing models.

2.3 Wing Design and Manufacturing

Using the design specifications indicated from the DOE, we modeled each wing in SolidWorks. The wing structure comprised leading edge, the inner spar, and up to two outer spars, depending on the configuration. The wing structure was made of Vero White using an Object Eden260V 3D printer where two copies of each wing were created. A soft and flexible low-density polyethylene (LDPE) 0.03-mm-thick plastic was used for the wing skin, which was tautly stretched and taped to a solid surface. The LDPE is adhered to the wing structures using Loctite adhesive and allowed to set before the wing shape is cut using a razor blade.

There are many methods available to achieve a distinguishable speckle, including patterned paper adhesives and water-soluble temporary “tattoos.” Spray paint is used to create the speckle for simplicity purposes and to maintain minimal skin thickness. Unfortunately, the effect of adding the paint to the LDPE is unknown since the wing must be painted to be tested. To achieve an even background, the wing is first coated with a thin layer of flat white spray paint, and then a fine mist of flat black spray paint is layered over the white to achieve the desired speckle pattern. A good speckle has dots similar in size and evenly distributed, and has about a high contrast, 50-50 ratio between black and white areas (*7*), as shown in figure 8.

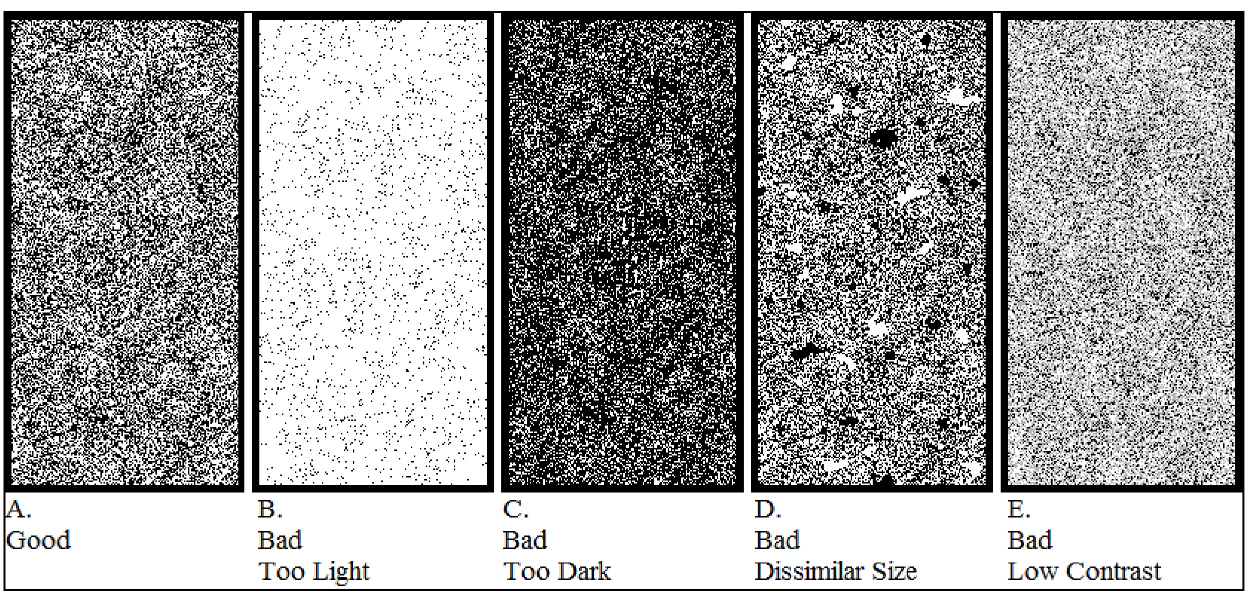

Figure 8. Speckle reference.

2.4 Experimental Setup and Process

Due to limited laboratory space, the DIC tests and load cell tests are run separately. For the DIC tests, the actuator is mounted on a clear, stable stand (figure 9) designed by Miles C. Pekala (*8*). The vibration of the actuator is tuned to match the wing's resonant frequency, causing the largest wing displacement. This frequency is noted for each wing design to ensure the same frequency is matched in the load cell portion of the test. The high-speed Photon cameras are set up at 20° angles to each other to view the specimen in stereo at 2000 fps. The cameras are calibrated, and after the wing motion is steady, about 2 s of data is collected, resulting in about 20 entire wing flap motions. This process is done for the 12 sets of wings. Once the frames are acquired, they are processed through the Vic-3D software, which will give strain, position, velocity, and acceleration data for each wing design.

The load cell portion of the experiment is set up using an optics board to mount the load cell. The actuator fits directly into the load cell mount, and again the vibration of the actuator's PZT material is adjusted to match the wing's resonant frequency. All of the load cell's strain gages are connected to the voltage meter to record the resulting thrust and lift generated from the flapping wings. Each set of wings is tested for about 10 s. and the voltage readings are recorded and saved.

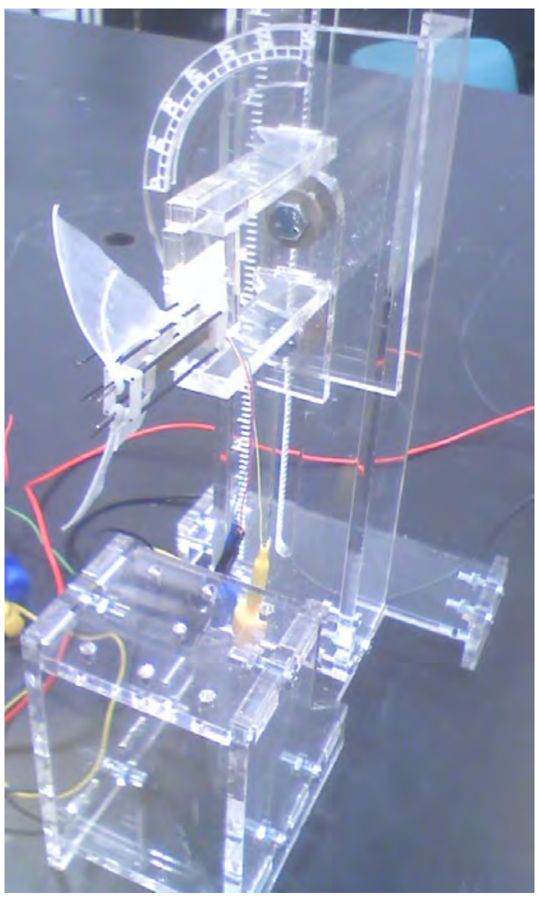

Figure 9. DIC wing mount.

3. Results and Discussion

Trends between the wing design parameters and performance will be examined and compared to previous research (*6*, *9–12*). Similar wing designs will also be tested using the test setup described here and to verify test performance results. In-depth computational analysis of the same wing designs will be able to validate project results, and providing an accurate model will be used to optimize and provide a final wing design.

4. Summary and Conclusions

The goals of this project are to gain a better understanding of small flapping wing motion. This is done by designing and documenting the process of analyzing small flapping wings with the DIC system and by building a load cell that can resolve minute stresses. This data will be used to validate a computational model that will assist in further design optimizations.

Specifically, there is interest in understanding the amount of strain, stress, and load experienced by the wing as well as what portion of the wing is under the most strain, stress, and load. Once the trends in the wing deformations are known, how the wing shape affects strain, stress, and loads will be determined. How the wing shape affects the wing position, velocity, and acceleration can be resolved, which will lead to the determination of the best wing shape.

The accuracy of this project data will be verified by comparing the results to computational models and simulations as well as historical data and other similar research projects. Upon completion of the testing and data analysis, we will recommend a final wing design and document the DIC testing process to aid in further testing.

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